The Next Wave of Digital Innovation: Opportunities and Challenges

Report on the Research Workshop:
"Digital Challenges in Innovation Research"

by

Youngjin Yoo[1]
Kalle Lyytinen[2]
Richard Boland[2]
Nicholas Berente[3]
James Gaskin[2]
Doug Schutz[1]
Nikhil Srinivasan[2]

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Information Systems Department
Weatherhead School of Management
Case Western Reserve University

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[1] Fox School of Business & Management, Temple University, Philadelphia, PA, USA.
[2] Weatherhead School of Management, Case Western Reserve University, OH, USA.
[3] School of Information, University of Michigan, Ann Arbor, MI, USA
[4] A 3-dimensional model of chaotic Mandelbrot set as an image of chaotic, emergent, and unbounded digital innovations.

Executive Summary

The turn of the millennium is marked by rapid developments in digital technologies. The ubiquity of digitalization is one of the primary forces behind innovations across a wide range of product and service categories. In order to create an initial forum for scholars from different fields, and to establish a preliminary theoretical framework that can guide future scholarly research on digital innovations, we organized an interdisciplinary research workshop, entitled "Digital Challenges in Innovation Research", held on October 18 – 20, 2008 at Temple University. This report documents major themes from the workshop, highlighting the new opportunities and challenges associated with digital innovation. Participants of the workshop were asked to address four questions:

1) What are the critical issues and opportunities for innovation associated with emerging digital technologies?
2) What are the organizational, technological, social and economic implications of these issues, and what generative processes of innovation and change emerge from them?
3) What theoretical constructs, research models and methodological tools will help us better study emerging issues in digital innovations? And,
4) What are the nascent inter-disciplinary research challenges in this area that scholars should consider in the future?

Digital Innovation in Architecture, Engineering and Construction (AEC). A central example used in the workshop was how the digitization of building models enabled a convergence of technologies and work practices across multiple trades and professions in AEC. The underlying technologies act as a shared digital infrastructure – a platform that binds heterogeneous actors together. This has led to additional, second order innovations as other digital tools became interwoven on the platform, forming complex digital work ecologies. As a result of this digitization, knowledge in AEC is increasingly changing from wet to dry forms as it migrates from humans into digital tools and products. Their digital work ecology now contains both material and semiotic relationships that span multiple social worlds. In AEC, this digitalization has led to wakes of innovation marked by a constant reconfiguration of roles, relationships, practices and identities among actors.

Digital Innovations. The workshop participants identified three design characteristics of digital technology that play pivotal roles in facilitating digital innovations: (1) the homogenization of digital data, (2) the programmable digital computing architecture, and (3) the self-referential nature of digital technologies. Furthermore, the participants saw digitalized products as having seven material properties: *programmability*, *addressability*, *senesability*, *memorability*, *communicability*, *traceability*, and *associability*, which lead to the emergence of loose coupling across the four layers of a *digital service architecture*, which includes devices, networks, services and contents. Before digitalization, these four layers were either tightly coupled within a particular media, industry or product boundary, or, in the case of purely physical or mechanical products, such layers simply did not exist. As a result of digitalization, however, these four layers can become de-coupled or loosely coupled through the integration of general purpose computing and networking. Taken together, this emerging structure suggests six new dimensions of digital innovations. They include: *convergence*, *digital materiality*, *heterogeneity*, *generativity*, *distributed locus of innovation*, and *accelerated pace*.

New Opportunities and Challenges. The main challenges and opportunities for *innovation outcomes* emerge primarily from convergence and digital materiality. First, new research opportunities lie in understanding different forms and capabilities of ongoing digital convergence. Second, another set of research issues are associated with new entrepreneurial opportunities that emerge from embedding digital capabilities into non-digital products and services. Finally, the increased use of digital tools and the interpenetration of digital and physical materiality in work practices offer new sets of challenges and opportunities that need to be carefully investigated.

The primary factors that affect *innovation processes* are heterogeneity, generativity, locus of innovation and pace. First, the combination of heterogeneity, generativity, and distributed locus of innovation leads to the emergence of dynamic, non-linear patterns of digital innovation. Developing and validating analytic models to understand how heterogeneous actors at the periphery of digital innovation networks are related to innovation patterns will be an important challenge for innovation scholars. Second, understanding the temporal dynamics of digital innovations provides another important opportunity for future innovation research. Finally, future research should investigate the multi-layered nature of organizational transformations that are associated with the digitalization of products.

Recommendations for Future Research. We make six broad recommendations:

Multi-disciplinary Research: Studying the emerging phenomena of digital innovations requires multidisciplinary research approaches that include scholars from at least three domains: the subject domain field, digital technology, and socio-economic theories of change and innovation. Such multi-disciplinary teams of scholars can pursue research projects with significant social and economic implications in the areas such as energy, environment, public infrastructure, transportation, and healthcare.

Design Scholarship: We believe research on digital innovation necessarily needs to take the form of what H. A. Simon refers to as the Science of the Artificial (Simon 1996). Design scholarship explores the creation of plausible, desirable alternatives and asks "*what might be*?" instead of trying to describe "*what is*."

Multi-methods Approach: Scholars studying digital innovations must be able to account for complex, emergent, and non-linear aspect of digital innovations, as well as see emerging patterns and orders. We need more thick, empirically grounded, theory-generating, qualitative research as well as quantitative research studies taking advantage of the unprecedented volume of data from the proliferation of digital artifacts in products and services. At the same time, we need to produce timely results, given the accelerated pace of digital innovations. Recent theoretical and methodological developments in computation techniques such as complex adaptive systems, network analysis, and sequence analysis are likely to yield useful insights.

Taking Data Seriously. One of the main research opportunities is the availability of unprecedented amounts of data generated from all types of digital artifacts, which, if properly regulated and managed, can lead to unprecedented insights on human behaviors in our increasingly complex socio-technical world. Scholars should to try to assemble large-scale, ultra rich data sets from the pervasive digitalization of our social and economic activities and make them available in the public domain to support more systematic scholarly activities.

Infrastructure. Many of the opportunities of digital innovations are based on the continuing availability and growth of a digital infrastructure. Scholars must pursue more systematically how infrastructure innovations emerge and how they in turn spur innovations in other areas.

Theorizing Digital Technology. Digital innovations imply that many of the economic sectors that are currently classified as separate sectors might need to be considered together. Current popular industry classification schemes such as NAICS and SIC codes however do not reflect the pervasive and ubiquitous nature of digital technology in a coherent way. We need a complementary classification scheme that reflects a digital architectural perspective, rather than our traditional product-centric view that assumes tight coupling across different layers.

1. Introduction

The turn of the millennium is marked by rapid developments in digital technologies such as pervasive computing, digital convergence, Web 2.0, service-oriented architectures, cloud computing, and the open source revolution. These and many other emerging digital technologies are re-shaping organizations and markets, creating technological discontinuity that disrupts traditional industry boundaries and business models (Benner 2010; Rothaermel and Hill 2005; Tilson et al. 2010; Yoo 2010). In this ongoing industrial and economic transformation, the ubiquity of digitalization is one of the primary forces, *tout court,* behind continuing innovations (Lyytinen and Yoo 2002; Weiser 1991). From global broadband and mobile infrastructures to pervasive use of RFID chips; from smart power grids to electronic patient record systems; and from a new generation of enterprise systems to millions of YouTube videos, digital technology is now a primary source of innovations. It introduces novel organizing logics, new products, and creative services that help address many of challenges of our time, big or small. In response to the current economic crisis, the U.S. government has placed digital technologies into a central position in promoting its future innovation policy (Executive Office of the President 2009). In fact, four of the President Obama's five "pillars" for future economic strength[5] requires the development and deployment of digital technologies. Therefore, it is no wonder that digital innovation is capturing increasing imaginations of scholars, consultants, business leaders, and policy-makers.

Although the debates and discussions are clearly not settled, there are certain principles that we can elicit from the emerging body of scholarly work focusing on digital innovation. Research is scattered across different disciplines and findings in one field often go unnoticed by scholars in other field. In order to create an initial forum for scholars from different fields, and to establish a preliminary theoretical framework that can guide future scholarly efforts on digital innovations, we organized an interdisciplinary research workshop, entitled "Digital Challenges in Innovation Research" on October 18 – 20, 2008. This report documents major themes from the workshops, highlighting the new opportunities and challenges associated with digital innovation. The workshop was co-hosted by the Institute of Business and Information Technology at Temple University and the Information Systems Department at Case Western Reserve University, and was supported in part by a grant from the National Science Foundation's Innovation and Organizational Sciences Program (NSF grant # 0621262).

We invited leading scholars who are studying different forms of digital innovation in diverse contexts with different theoretical perspectives and research methods (see Appendix A for a participant list). The workshop brought together 42 international scholars from information systems, computer science, organization science, and economics for three days to explore the opportunities and challenges associated with research on digital innovation. Extended abstracts of presentations at the workshop are available at http://innovation.temple.edu/workshop08/. Participants of the workshop were charged with addressing four questions:

1) What are the critical issues and opportunities for innovation associated with emerging digital technologies?

[5] President Barack Obama speech, April 14, 2009, Georgetown University, http://www.nytimes.com/2009/04/14/us/politics/14obama-text.html?pagewanted=1&_r=3

2) What are the organizational, technological, social and economic implications of these issues, and what generative processes of innovation and change emerge from them?
3) What theoretical constructs, research models and methodological tools will help us better study emerging issues in digital innovations? And,
4) What are the nascent inter-disciplinary research challenges in this area that scholars should consider in the future?

By *innovation*, we mean the creation and adoption of an idea, a product, a technology, or a program that is new to the adopting unit (Gupta et al. 2007). By *digital innovation*, we mean an innovation enabled by digital technologies that leads to the creation of new forms of digitalization[6]. By *digitalization*, we mean the transformation of socio-technical structures that were previously mediated by non-digital artifacts or relationships into ones that are mediated by *digitized* artifacts and relationships. Digitalization goes beyond a mere technical process of encoding diverse types of analog information in digital format (i.e., "digitization") and involves organizing new socio-technical structures with digitized artifacts as well as the changes in artifacts themselves.

The rapid miniaturization of computer and communication hardware, combined with their ever increasing processing power, storage capacity, communication bandwidth and more effective power management have made it possible to increasingly and pervasively digitize previously non-digital artifacts (Brynjolfsson and Saunders 2009; Kurzweil 2006) across different industrial and organizational contexts (Tilson et al. 2010; Yoo 2010). When this reshapes the underlying value propositions, we refer to it as digital innovation. An example of digitization that is merely technical is when the telecom industry installed digital switching in the 70's, which did not change the socio-technical context. In contrast, examples of digitalization and its disruptive transformations are mobile media, Internet-based TV, digital publication, and digital cameras. In these examples, significant innovation involved not only the digitization of artifacts such as mobile phones, TVs or books, but also a much broader socio-technical reordering of organizing logics among heterogeneous firms that are newly interconnected through a common digital infrastructure.

The report is organized as a review of salient themes raised during the workshop. We performed qualitative data analysis that involved coding and categorization of transcripts of workshop presentations and roundtable discussions. We complement our analysis of the workshop transcripts with a summary of recent research, including our own, on digital innovation. Throughout the report, we cited workshop participants using square brackets with [presenter], and use conventional parentheses with (author, year) to cite published works.

The remainder of the report is organized as follows. First, we review our ongoing research program on digital innovations in the Architecture, Engineering and Construction (AEC) industry, and why it motivated us to seek generic patterns of digital innovation in the wider economy. Then we present a broader analysis of digitalization and its relationships to innovation. In particular, we explore characteristics of the current wave of digital innovation, followed by a summary of the key findings from the workshop organized around innovation outcomes and processes. There, we pay particular attention to actionable knowledge for theory development, methodological adaptation, and technology development (including both

[6] This definition excludes the impact of using word-processor instead of a typing machine in writing product documentation as a form of digital innovation.

new forms of services and technologies enabling cyber-infrastructure). Finally, we translate the key findings and insights from the workshop into a set of recommendations for scholars who want to study digital innovations in the future.

2. Digitalization in the AEC industry: A Prolegomena to Digital Innovation

The workshop was inspired by our experiences in carrying out a series of NSF-funded research projects since 2003 (NSF grants #0208963, #0621262, #0943157 and #0943010)[7]. In our research program, we have been studying digital innovation in the AEC industry. We have examined the impact of digital technologies on both building design and construction tools and techniques, and the subsequent embedding of digital capabilities in diverse work practices across the AEC industry.

We have examined the consequences of using three-dimensional computer-aided design (3-D CAD) systems and, more recently, Building Information Management (BIM) systems. Our study reveals that these tools not only improve the efficiencies of the design and construction processes, but also act as catalysts for “wakes of innovations” among heterogeneous firms and communities in terms of tools, methods, knowledge, processes and designs changing along the way the very meaning of buildings, trades and their identities (Boland et al. 2007; Yoo et al. 2006). In short, the process of digitalization is dynamic, chaotic, multipath and expansive.

Digital innovation in the AEC industry has had several significant consequences for the design and construction of buildings. First, the digitization of building models and data has created a *convergence* effect that has brought together traditionally separate and unique models and data from different trades and communities. In this convergence, models and data from diverse sources that serve vastly different design and construction purposes can now be collated, integrated and triangulated. The digital convergence of AEC knowledge and its representations led to an increased social and technical convergence among the many actors in AEC projects, and changed their relationships from arms-length transactions to much closer collaborations.

Second, the underlying 3-D CAD and BIM systems act as a shared digital infrastructure that binds heterogeneous actors together. The digital infrastructure makes previously unconnected actors, who often have conflicting goals and interests, increasingly dependent upon each other. This convergence, in turn, has lead to additional, second order innovations across different trades as the 3-D CAD and BIM systems provided a platform on which other technologies (such as 3-D survey tools, CNC fabrication tools, project management tools, etc) become interwoven, forming complex digital work ecologies. These ecologies enable new types of “trading zones” (Galison 1997), in which actors can collaborate by trading diverse, incommensurable knowledge across organizational and craft boundaries. Through these trading zones, innovative ideas traverse between actors in different social worlds in unpredictable ways, creating multiple, wake-like patterns of innovation (Boland et al. 2007). Unlike traditional forms of vertical integration, these digital ecology innovations maintain technological and organizational heterogeneity and actor autonomy. What is striking in our

[7] See Path Creation at http://info.cwru.edu/path, Digital Innovation at http://innovation.temple.edu/, and Virtual Design DNA at http://designdna.case.edu.

findings is the decisive role that digital technology plays in linking previously unconnected actors and offering new possibilities to create “wakes of innovation”.

Third, through digitalization, knowledge is increasingly changing from *wet* to *dry* forms[8] as it becomes increasingly embedded into digital tools and products. These digital artifacts now contain both material and semiotic relationships that span multiple social worlds. As a result, AEC project knowledge has become increasingly accessible in diverse forms across multiple social worlds. Embedding knowledge in these artifacts leads to fundamental changes in the way individuals interact with and through them (Berente et al. forthcoming).

Finally, this digitalization has led to a constant reconfiguration of roles, relationships, practices and identities among actors (Berente et al. 2007; Tripsas 2009; Yoo et al. 2006). We have observed the generativity (Zittrain 2006) and the unbounded nature of digitalization (Hanseth and Lyytinen 2010; Henfridsson et al. 2009). Digital platforms invite other actors to join in networks that explore and exploit new entrepreneurial opportunities. The malleability of digital technology allows entrepreneurs to seek new economic and technological opportunities unforeseen by the firms who originally invented it (Yoo 2010).

As we progressed in our research program on digitalization in the AEC industry, we became increasingly aware of similarities between digital innovations in AEC and other industries, including mobile services, media, software development and automotive. Although it may appear that different types of digital innovation take place in different industries, many times their forms are in fact imbued with the same underlying generative logics. This led us to ask workshop participants to explore the generative logics and formative patterns of digital innovations across multiple industries and settings.

3. Digital Innovation: What’s New?

A question throughout many of the workshop discussions was simply: does digitalization introduce anything novel to innovation that makes digital innovations fundamentally different from non-digital innovations. While opinions of the participants were mixed, most participants agreed that certain characteristics of digital innovation are distinct. Moreover, these characteristics are often combined into new forms of innovation that are unique and transformative. In order to understand what makes these new forms of innovation possible, we first need to discern the essential characteristics of digitalization that make an innovation process a generative and unbounded one, without falling prey to simplistic versions of technology determinism.

3.1. Digitalization and Digital Materiality

Our starting point is the observation that ongoing digitalization in our material world adds new material properties to previously non-digital, industrial age products and processes. To address the interaction between digital and non-digital materiality, we identified the unique design characteristics of digital technologies and the properties that digitalization affords. We then describe a generic service architecture and how it relates to three “waves” of digitalization.

[8] Human body and brains are nearly 90% water, while there is 0% water in silicon.

3.1.1. Design characteristics of digital technology

Three design characteristics of digital technology that play pivotal roles in facilitating digital innovations and their unique consequences include: (1) the homogenization of digital data, (2) the programmable digital computing architecture, and (3) the self-referential nature of digital technologies. Next we will address each in turn.

First, unlike an analog signal, which maps changes in one continuously varying quantity onto changes in another, a digital signal transforms analog signals into numbers and ultimately bits (a contraction of binary digits) (Tilson et al. 2010). There is a tight coupling between analog data and analog devices, such as in vinyl records or VHS tape, in which matching special purpose technologies of production and distribution are required. As Tilson et al. (2010) note, a tight coupling between data and device led to the emergence of vertically integrated industry structures for analog media. However, through the digitization of analog data, any type of content (audio, video, text and image) now can be stored and transmitted using the same device. Once digitized, data from different sources can be transformed and manipulated and further combined with yet other data, dissolving the boundaries between different media.

Second, based on the Von Neumann Architecture, modern digital computers use a processing unit and a storage unit to hold both instructions (programs) and data in the same format and the same locations. Modern digital computers shift between handling bits as data and bits as the instructions for manipulating that data. This provides a remarkable flexibility to perform many different functions (like calculating, word processing, video editing and web browsing), all with the same device. Thus, technical digitization of previously non-digital artifacts leads to the separation of the semiotic logic of a program and the physical hardware device that performs it. Unlike non-digital devices, digital artifacts can be flexibly programmed and re-programmed.

Third, digital innovation requires the use of digital technology. This self-referential nature of digital innovation means that wide spread diffusion of digital innovation requires ubiquitous access to digital tools, such as PCs as a design platform and the Internet as a communication network. Ubiquitous access of digital technology accelerates the diffusion of digital tools, creating network effects. As the price-performance and performance-size ratios of digital computers continue to improve overtime, connecting them in a global data network (the Internet) creates a powerful feedback condition that further accelerates the creation and diffusion of digital innovations. By the late 1990's, PCs and the Internet became accessible to unprecedented number of users, who could experiment with different forms of innovations. Unlike industrial technologies that require extensive capital to acquire, users could more readily access digital technology platforms. This in turn opened a floodgate of new types and forms of innovation (Tuomi 2002; von Hippel 2005).

These three design characteristics – *homogenization of digital data*, *programmable digital computing architecture*, and *self-referential nature of digital technologies* – form a powerful set of reciprocal and mutually re-enforcing forces that have created the unique socio-technical dynamics of digital innovations, as we will review later in the report.

3.1.2. Properties of digital materiality

Digitalized artifacts have a variety of material properties that differentiate them from their non-digital counterparts. Seven such properties were noted at the workshop (Yoo 2010).

- **Programmability**: At the most fundamental level, small, low-power microprocessors make it possible to embed programmable digital architecture into what used to be fixed, mechanistic, non-digital artifacts. The feature of *programmability* refers to the ability of a now digitized artifact to accept new sets of instructions and to modify its behaviors. This makes digital artifacts able to perform additional and extensible functions, above and beyond their original purpose, thus making them malleable (ITU 2005).
- **Addressability:** Programmable memory chips (e.g. RFID) make individual artifacts addressable, which means that each digitalized artifact can be uniquely identified within a particular context. This feature of *addressability*, together with programmability, brings more digitalized artifacts into the global information infrastructure, moving towards an Internet of Things[9].
- **Senseability:** The integration of sensors enables artifacts to recognize and record multiple types of information about their environment. Here, *senseability* refers to the ability of a digitalized artifact to sense and respond to changes in its environment, making it context aware (Dourish 2001). Senseable artifacts form an edge of the digital infrastructure that is constantly evolving.
- **Communicability:** Digitalized artifacts interact with other artifacts, infrastructures, and actors through embedded communication capabilities. Their *communicability* refers to the ability of a digitalized artifact to send and receive digitized messages. Combined with senseability, their communicability generates new relationships between actors and artifacts. For example, individuals now connect sensors to their Twitter accounts in order to monitor their environment, homes, and even movements of a fetus in a mother's womb[10].
- **Memorability:** Digitalized artifacts will become increasingly memorable. *Memorability* refers to the artifacts ability to record and store information that it has generated, sensed, or communicated. As a result digitalized artifacts will have the capability to remember where they were, who used them, the outcomes of the interactions, etc.
- **Traceability:** Senseable and memorable artifacts, and new relationships among these artifacts and actors, will produce expansive digital traces of their conditions, properties, movements, and interactions, making them newly visible across time and space. The notion of *traceability* refers to the ability of a digitalized artifact to chronologically identify, store, and relate encounters with events and entities in time.
- **Associability:** New software innovations, such as the Semantic Web (Berners-Lee et al. 2001) enable knowledge associated with actors, artifacts, places and events to become associable and inferable, making folk based knowledge more widely sharable. The idea of *associability* refers to the ability of digitalized artifacts to be related to and identified with other entities (such as other artifacts, places or people) and to enable inferences about future states and conditions. This property enables de-centralized and intelligent forms of organizing, sensing and acting in the world with a minimum intervention of centralized control.

3.1.3. A four-layered generic model of digital service architecture

An important consequence of the digitalization of products and services is the emergence of a generic model of digital service architecture with four layers: devices, networks, services, and

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[9] See e.g. http://en.wikipedia.org/wiki/Internet_of_Things

[10] Twitter (http://twitter.com) An internet-based short text message broadcasting service up to 140 characters.

content (Figure 1) (Benkler 2006). The device layer is further divided into a physical machinery layer (TV, PC, mobile phone, car, etc) and logical capability layer (operating system), which provides control of the hardware device. The network layer is similarly divided into a physical transport layer (including cables, radio spectrum, transmitters, etc) and a logical transmission layer (including network standards such as TCP/IP or P2P). The service layer deals with application programs that directly interact with users as they create, manipulate, store and consume different content. With the service layer, users can listen to music, send and receive e-mails, read books, watch videos, and receive navigation information. Finally, the content layer includes the actual data such as texts, sounds, images, and videos. The content layer can also contain meta-data including ownership, copyright, encoding methods, content tags, and geo-time stamps. This type of multi-layered architectural stack is not new to computer and network technologies. What is new here is how this four-layered architectural view of digitalized service will become more broadly applicable to all types of products.

Before digitalization, these four layers were tightly coupled together within a particular media, industry or product boundary. Or, in the case of purely physical or mechanical products (such as furniture, car, hammer, and clothes), such layers simply did not exist. However, as a result of digitalization, these four layers can be de-coupled, or loosely coupled, through the integration of general purpose computing and networking capabilities.

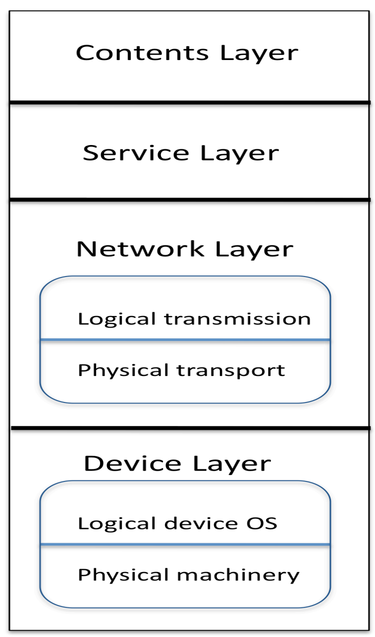

Figure 1. A Four-layer Generic Model of Digital Service Architecture

The emergence of the four-layered digital service architecture has pronounced strategic and structural implications. How open or closed this architecture is and how firms control the architecture reflects a collection strategic decisions.

3.1.4. Three waves of digitalization

Historically, digitalization takes place in three stages. The first wave of digitalization involves the technical digitization of converting analog contents and services into digital ones without fundamental changes in the industry structure. Examples of the first wave of digitization includes the transition from 1G to 2G cellular network and the emergence of CD in the music industry (Tilson et al. 2010). In the first wave, the industry experiences significant cost reduction with "more of the same" services, following the image of "paving the cow paths" (Tilson et al. 2010). The first wave of digitalization does not bring any fundamental changes in the tightly coupled layer of product architectures.

In the second wave of digitalization, we begin to see the separation of devices, networks, services, and contents that have been tightly coupled in the past. Digitalized contents and services now can be provided through a general purpose IP network and software-enabled devices, which leads to a convergence at multiple levels including network, device, and market. As a result, traditional boundaries across product categories and industries are constantly shifting as seen by recent innovations like Voice over IP (Benner 2010) and Digital TV (Tilson et al. 2010). For example, voice service becomes completely independent of device and network, and the same quality voice service can be delivered whether the user is using a fixed line phone, a desktop computer, or a mobile phone. Similarly, other media services, such as music, books, e-mail and movie can be delivered over multiple different types of networks using multiple devices.

In the third wave of digitalization, we begin to see the emergence of novel products and services through the "mash-up" of different media across different product architectural boundaries. Devices, networks, services, and contents that were created for specific purposes are now being re-mixed in order to repurpose their usage (Lessig 2008; Tilson et al. 2010). For example, location stream services such as Yahoo's Fire Eagle (http://fireeagle.yahoo.net/) can be mixed with other services and contents. Similarly, one's social network information can be mixed with other types of services and contents. These mash-up services can be further re-combined creating a constant stream of innovation possibilities. Furthermore, small and powerful computing devices now can be embedded into previously non-digital artifacts, enabling new information services. For example, a simple insertion of an RFID chip into a pair of running shoes enable a runner to collect data (such as pace, location, and biometrics) that were not available in the past. Once captured, such information can be shared through one's social network services like Facebook or Twitter, or can be mashed-up with other media such as Google Earth or Flickr photo services. Or one's own running record can be simply juxtaposed with others' records.

As a result, in the third wave, vast amounts of information that used to be invisible can now be captured, and related to a layer of semiotic logic. By separating a physical, non-digital artifact from its semiotic logic and network layers through digitization, we enable a loose coupling of the four layers in a digital service architecture and form the basis for continuing innovations in the third wave of digitalization.

The emerging innovations of the third wave differ from earlier innovations that either eliminated or simplified physical tasks through automation (e.g. digital switching) or improved efficiencies of repetitive tasks through more effective processing of information (e.g. payroll). The primary impacts of these early forms of digitization were limited to productivity improvements on the factory floors (Zuboff 1988) and in the performance of knowledge workers (Brynjolfsson and Saunders 2009; Campbell-Kelly 2003). In the recent waves of digitalization, we are increasingly witnessing a new fusion of various types of digital innovations through the integration and mobilization of all seven features of digital materiality. As a result, simple products such as coffee tables or more complex ones like cars now have embedded computer and communication capabilities [Henfridsson & Mathiassen].

Similarly, physical and repetitive tasks are being augmented with rich digital traces and the use of intelligent digitalized tools [Lyytinen]. In principle, an all-encompassing digitalization can integrate all the seven properties of digital materiality with every action, behavior and task in our life. Traces of physical actions, events and movements in the physical, social, and virtual worlds can be digitally stored, tracked, monitored, processed and re-processed at unimaginable scale and relentless pace. The industrial age was a call to efficiently perform physical tasks; the present age is a call for digital models and tools to perform semiotic processes with global observability and analysis [Garud, Kumaraswamy & Tuertscher]. The outcomes is a growing stream of digital data concerning organizational life, products and services that is creating a huge 'data deluge' [Bowker].

3.2. New dimensions of Digital Innovation

An underlying theme during the workshop was how the seven properties of digital materiality and the emergence of loosely-coupled digital service architectures have stimulated waves of digitalization that are fundamentally re-shaping innovations in products, services and organizational forms. For example, a workshop participant observed that digitalization is "rewriting law, standards of social conduct … in attempts to give away intellectual property as a means to profit from it while users distribute innovations based on that intellectual property for you" [Jarvenpaa]. Another participant noted that as a result of increased senseability and communicability of products, "control is changing in organizations and it's fundamentally changing increasingly into network-based organizations" [Henderson]. Other participants suggested the need to "re-think our innovation infrastructure to address a new asymmetry of novelty" created by mixing diverse social worlds with new digital traces, representations and communications [Carlile & Lakhani]. Finally, several participants argued that new forms of organizing for innovation became possible as the scale of digitizing drove down communication cost [Cummings; Faraj; Lakhani & Gulley; Malone].

Our analysis of the workshop transcripts identified six dimensions of digital innovation: (1) convergence, (2) digital materiality, (3) generativity, (4) heterogeneity, (5) locus of innovation, and (6) pace. These are summarized in Table 1 and will be discussed below in more detail. The six dimensions are associated with both innovation outcomes (convergence, and digital materiality) and innovation processes (generativity, heterogeneity, locus of innovation, and pace). These six dimensions are not mutually exclusive. Rather, they interact and reinforce each other in an ongoing virtuous cycle of digitalization, increasing the complexity and dynamism of innovation outcomes and processes.

Table 1. Six Dimensions of Digital Innovation

Dimensions	Descriptions
Convergence	Continuous integration of diverse and heterogeneous technologies through homogenization of digital data; multi-modality of technologies; and layered, loosely coupled connections across devices, networks, services and contents.

Digital Materiality	Inseparability of digital material from social and physical interactions; loose coupling of physical materials and semiotic logics; embedding of digital capabilities into physical artifacts; emergence of digital service architecture for previously non-digital products and services.
Heterogeneity	Integration of diverse forms of data, information, knowledge, and tools; intensified need to coordinate across multiple social and technical worlds; increased horizontal integration across different stacks of digital service architecture.
Generativity	High degree of equivocality, enabling continual reinterpretations, expansions and refinements of products and services; design characteristics of digital representations that foster unbounded innovations through incessant recombination and modification of different elements in digital service architectures; pervasive diffusion of digital tools and low cost communication enabling wakes of innovations.
Locus of Innovation	Dramatic geographical and social dispersion of innovation sites and processes due to low communication and storage cost; independent innovation trajectory at different layers of digital service architecture; increasing movement of innovation activities toward the periphery of the innovation network.
Pace	Increase in the clock speed of innovation cycles due to programmability and convergence; increased velocity of innovation due to re-combination as a mode of innovation; accelerated pace of innovation due to a common digital infrastructure facilitating distributed innovation activities.

3.2.1. Convergence

The growth of digitalization has made digital convergence a reality (Lyytinen and Yoo 2002; Yoo 2010). Digitized technologies share the same infrastructural capabilities, which opens novel opportunities for products and services (Tilson et al. 2010). Digital convergence enables the combination and re-combination of devices, networks, services and contents that were originally created for different purposes. As the four-layer digital architecture becomes more loosely coupled, digital representations within and across these layers can be manipulated and re-combined in ways that create new families of representations *ad infinitum*. Through this re-combination process, digital convergence creates a space for previously unforeseen combinations of digital representations and capabilities to emerge [Zahra, Bhawe & Gupta] (see Figure 2). For example, so-called 'triple-play' (combining broadband internet, phone and TV services) or 'quadruple-play' (adding mobile internet) is an outcome of digital convergence in media content, storage and distribution mechanisms. Similarly, digital convergence has created major innovations such as iTunes, YouTube, or Slingbox.

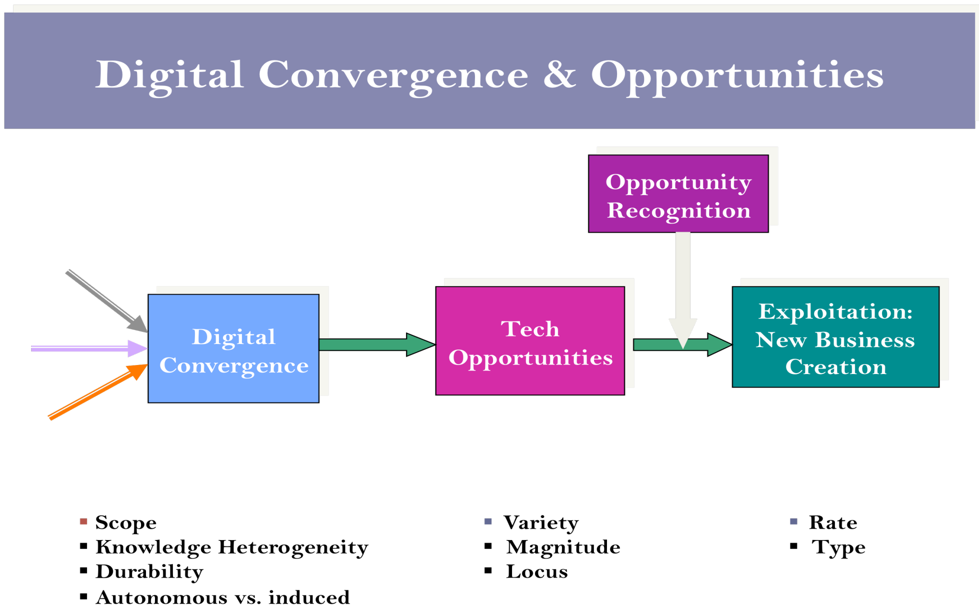

Figure 2. Convergence and entrepreneurial opportunity identification [Zahra, Bhawe & Gupta]

The impacts of digital convergence are not limited, however, to communication and media. Many artifacts that were non-digital now include digital components enabling them to interact with other digital devices, to connect to the Internet, or to interact with the environment in which they operate. This offers organizations and innovators new ways to differentiate customer or user experience. For example, GPS (Global Positioning Systems) service in digital cameras and mobile phones, when combined with comprehensive digital maps and sensors in buildings, cars or clothing, feeds a stream of service and product innovation that connects previously unconnected user experiences and creates a new kind of virtual physical world.

Digital convergence also changes the nature of products towards becoming digital platforms. Increasingly, firms establish digital service architectures for their products and strategically control them as part of their innovation trajectories. For example, most subsystems of an automobile have become digitized and connected through vehicle network systems. As a result, an automobile has become a mobile computing platform, on which new services, contents, networks, and devices can be developed - often by companies coming from outside of the traditional automotive industry [Henfridsson & Mathisassen].

Finally, digital convergence affects the process of developing products and services as well. For example, in the AEC industry, new digital tools allow designers to digitize not only the building drawings, but also other aspects of construction management such as site measurements, survey data, fabrication data, cost estimates, data about risk and time, and construction knowledge [Lyytinen; Whyte]. Again, connecting previously unconnected data of the construction process creates a space to enact new types of innovation processes. Each time a connection is made between previously unconnected communities and their knowledge due to digital convergence, actors in these communities are likely to bring their technology capabilities and unique knowledge into the network opening a new space for a digital invention (Berente et al. 2007).

3.2.2. Digital Materiality

To begin to understand digital innovation, scholars must take digital materiality seriously. Effective research on digital innovation will consider both material characteristics of digital technology and broader socio-technical structures. Past research on innovation in the organization science literature has broadly neglected the unique material characteristics of digital innovation. As Lavie (2006) notes, “referring to technological change as an exogenous event is a conventional assumption in technological discontinuities research” (p. 154). Technology innovations are essentially black-boxed and described as a stochastic process (Anderson and Tushman 1990). Thus, the predominant focus in the literature is how to respond to exogenous technological change, primarily through structural prescriptions, such as creation of ambidextrous organizations (Tushman and O'Reilly 1999) or heavyweight teams (Clark and Fujimoto 1991).

Summarizing the literature, Benner (2007) notes that “*responding* to environmental change is a critical challenge for firms, and whether and how organizations *adapt* is a central topic in organization theory and strategy research” (p. 93, italic is ours). In short, the organization science literature should move beyond studies of reactive adaptation to disruptive changes and address the generative processes that drive digitalization.

Because organization science has tended to de-contextualize the material and social elements of digital technology (Hevner et al. 2004), scholars in the socio-technical system literature have long been promoting more nuanced treatment of social and material aspects of innovation (Bijker 1995; Bijker et al. 1993; Hughes 1983; Latour 2005; Latour and Woolgar 1979). Recently, materiality has received a greater attention in the context of digital innovation where products or services are IT enabled (Leonardi and Barley 2008; Orlikowski 2007; Orlikowski and Iacono 2000; Orlikowski and Barley 2001), with calls to consider how digital materiality is intertwined with physical materiality of products and process. As digital and physical materiality become intertwined, innovation scholars should consider how they mutually shape each other, and how they interpenetrate as they accommodate and resist human agencies (Pickering 1993; Svahn et al. 2009). The interface between physical and digital materiality, therefore, bears particular theoretical significance for future digital innovation research.

As organizations use digital technologies, they become increasingly virtualized. The material artifacts that individuals interact with does not consist of atoms alone, but also bits that always embody semiotic relationships with an environment. This inevitably adds a social dimension to the material world, at the same time that digital service architectures lead to an increasing dependence on models and data, with all seven properties of digital materiality. This raises new challenges of representing domains that were previously absent in digital models [Henfridsson & Mathiassen; Leonardi, Barley & Bailey; Whyte]. Finally, new features and capabilities enabled by digital materiality [Henfridsson & Mathiassen; Yoo; Zahra, Bhawe & Gupta] create entrepreneurial opportunities that will be a major avenue for future digital innovations. Unlike prior research on innovations that treated these material characteristics (both physical and digital) as being outside of their domain, future research on digital innovation will consider the interpenetration of physical and digital worlds, and how they become intertwined with human agency and social structure.

Accordingly, the study of digital innovation needs to address forms of organizing that enable seamless integration across the social, the physical, and the digital. An important issue is how digital materiality is generative to new socio-technical arrangements of products and services that are deeply embedded into everyday life experiences, and how the new digitally enabled capabilities of products and services might transform them (Yoo 2010). Whereas past research on information technology focused on the impact of “lifting out” social practices from the immediate and local context into a global and distributed realm (Giddens 1990), future research on digital innovation will emphasize how the digital interacts with the physical reality, including specific physical locations, concrete user interfaces and particular affordances. Exciting research opportunities lie in exploring how the new digital materiality is interdependent with human agency and broader institutionalized social structures.

Embedding digital materiality into products and services requires designing and managing digital service architectures and establishing architectural control points. An architectural control point refers to “a system component that enables or constrains the design of complementary components through visible information (e.g., interfaces) that can be manipulated by designers.” [Woodard & West]. By strategically managing the architectural control point, a firm can make the digital service architecture of a product more or less open or closed. Traditional models of coordination of innovation and architectural control followed organizational structures, which reflected hierarchical product architectures (Baldwin and Clark 2000). Such product architectures are based on tight coupling between physical or logical semiotic layers. This assumption is challenged by increases in lateral and loosely coupled relationships among digital components [Henderson; Woodward & West]. Given that digitalized products and services have both physical components and digital layers (Svahn et al. 2009), how we integrate the traditions of hierarchical control with more open coordination methods becomes an important challenge [Helper; Tuomi].

Finally, digital innovation involves both physical materiality (e.g. the time and place, the physical environment of the work and physical affordances of artifacts including hardware) and digital materiality (what one can functionally do with affordances offered by embedded digital capabilities). The latter is defined by the seven properties of digital materiality embedded into the product itself and the surrounding environments. In the context of digitalization, one expands existing physical materiality by ‘entangling’ it with new digital capabilities (Robey et al. 2003; Svahn et al. 2009). In any given socio-technical context, the physical materiality and the digital materiality are increasingly seen as mutually constituting each other (Law and Urry 2004; Robey et al. 2003). Continued socio-material digitalization of products and services requires that organizations leverage new knowledge resources and tools.

Due to the self-referential nature of digital innovations, these new resources require organizations to transform their work practices by adopting or inventing additional digital tools. However, like financial leverage, digital tools bear significant inherent risks that can lead to unintended consequences, particularly when the underlying model or data structure fails to accurately “reflect” essential elements of the physical materiality. For example, over reliance on digital models and rules is viewed as one of the key causes of the recent financial crisis. Similar risks are being observed in other areas like complex construction projects, or complex engineering projects where both physical and digital models are used [Leonardi, Barley & Bailey; Whyte] (see figure 3).

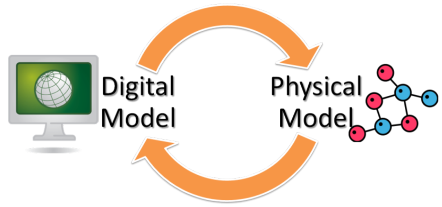

Figure 3. Interactions between the physical model and the digital model [Bailey & Leonardi]

3.2.3. Generativity

Generativity refers to the way actors, who were not directly involved in the original creation of a technology, begin to create products, services, and content that may not be consistent with the original purpose of the artifacts (Zittrain 2006). Generativity was posed as a direct consequence of digital representations: "the idea of digitalization as a representation in itself fosters and legitimates thinking about new ways of organizing / new ways of doing things" [Swanson]. The traceability of digital contents further supports generativity by enabling conversational production as an innovation process [Garud, Kumaraswamy & Tuertscher]. Furthermore, the generative power of digital capabilities encourages the development of digital platforms [Faraj], and allows increased flexibility, growth and change of them [Henderson]. In addition, it was noted that differences in professional liability and alignments [Bailey & Leonardi] and in the ownership and control of dispersed data [Jarvenpaa] mederate the level of generativity.

Higher levels of generativity permit higher rates of discovery of novel ideas, which leads to faster innovation cycles with increased iteration, which is a more dynamic, agile innovation process than the linear gate-based models widely used for controlling innovation. As innovation processes become more dynamic and agile, there is a "downward shift in iteration cost" that enables higher levels of exploration and reconfiguration [Austin] (see Figure 4).

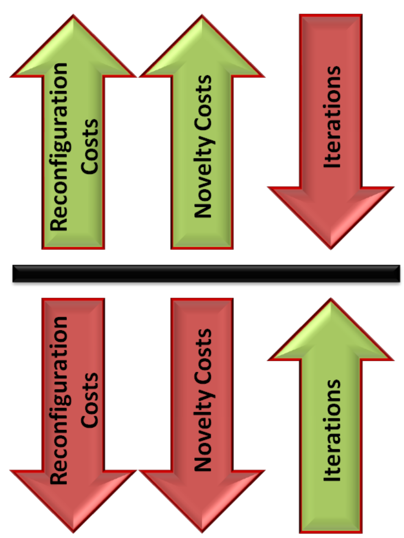

Figure 4. Cost drivers affecting generativity and iteration [Austin]

Faster iteration cycles reshape the knowledge creation process during digital innovation. Groups increasingly display the co-creation of ideas as digital innovation "facilitates tracking, sharing, consolidating ideas and frames, growth through group evolution, … fosters emergence not centralization" [Majchrzak, Birnbaum-More & Faraj]. Figure 5 shows the emergent process of knowledge co-creation in an iterative digital innovation process.

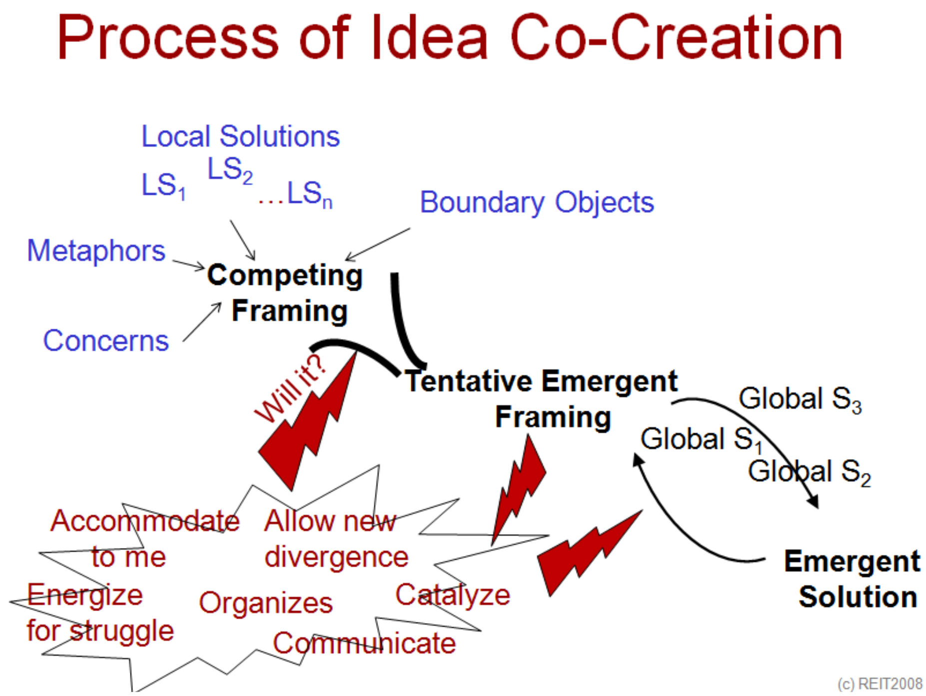

Figure 5. Iterative process of idea co-creation in digital innovation [Majchrzak, Birnbaum-More & Faraj]

3.2.4. Heterogeneity

Digital convergence combines resources and components in unforeseeable ways, requiring the integration of previously unconnected knowledge, activities, artifacts and capabilities [Yoo; Zahra, Bhawe & Gupta]. As designers, engineers, entrepreneurs and users envision new services, products and processes by drawing upon digital capabilities, they engage with foreign vocabularies, invoke unfamiliar tools and methods, and encounter equivocal and even contradictory social worlds. An important challenge resulting from convergence is then how to manage knowledge heterogeneity (Boland & Tenkasi 1995), especially as seen in the multiplicity of models and material practices of designers [Bailey & Leonardi], the data deluge [Bowker], and the struggles over data and innovation ownership [Jarvenpaa].

The challenge of heterogeneity is further complicated by the distributed nature of digital innovation. In the past, much innovation was centralized. Digital technologies, however, enable multiple forms of distributed intelligence as diverse autonomous actors co-produce innovation. Some examples of distributed intelligence in innovation are open source or platform initiatives like Linux, Google, Wikipedia, or Digg. Distributed intelligence is also evident in digitally mediated innovation contests such as Innocentive, Top Coder, and in averagers such as those used in prediction markets and NASA Clickworks [Lakhani & Gulley; Malone].

A firm can control the level of heterogeneity through architectural control points [Woodard & West]. As shown in Figure 6, different levels of architectural control points create different forms of innovation networks with different degrees of heterogeneity. If a firm can exercise strong control over its digital service architecture, the heterogeneity of the innovation network will decrease. In contrast, when a firm has less architectural control and allows loose coupling across the four layers of its digital service architecture, the heterogeneity of the innovation network will increase.

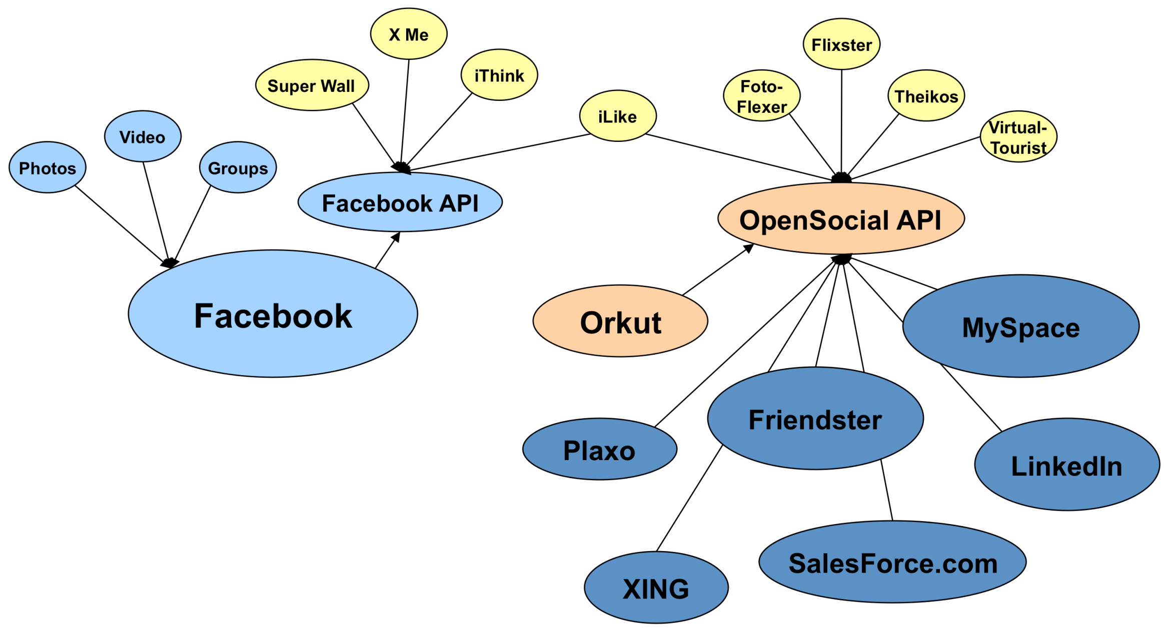

Figure 6. Comparison of Facebook and Google's Open Social [Woodard & West]

Another key question in research on digital innovation is how to leverage technical capabilities (with their inevitable incompleteness) during the innovation process in order to create increased levels of social heterogeneity [Garud, Kumaraswamy & Tuertscher; Henderson; Zahra, Bhawe & Gupta]. Combinative platforms and two-sided markets are seen as important in generate and sustain the social heterogeneity that helps drive innovation [Henderson]. Heterogeneity, combined with the generativity of digital innovation, can produce unbounded innovation with continuous cycles of innovations that are in response to a previously recognized opportunity lead to further innovations in a newly recognized one. Heterogeneity inevitably creates groups of innovators who face what Carlile & Lakhani identify as the "paradox of novelty", in that "knowledge is both a source and a barrier to innovation and … innovators must have both confirming and novel knowledge across people and artifacts for creating an innovation sweet spot" [Carlile & Lakhani].

Given the increased level of heterogeneity among innovators, what is known across disparate knowledge communities becomes asymmetrical, requiring N-dimensional learning capabilities to successfully navigate a Draconian knowledge labyrinth [Dougherty]. Such learning capabilities involve a delicate balance between the use of novel versus known knowledge that successful innovators need to master - on the one hand, too much novelty may lead to chaos, and on the other, too little novelty may lead to stagnation. (see Figure 7)

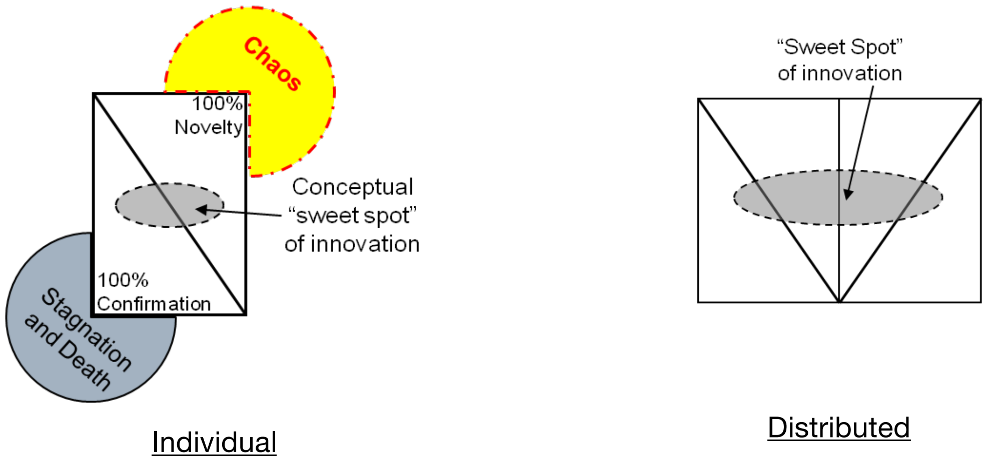

Figure 7. Innovation Sweet Spot [Carlile & Lakhani]

To overcome the challenges associated with increased heterogeneity, communities of knowing need to find new ways to coordinate (Boland & Tenkasi 1995). One strategy is to form digitally enabled trading zones (Boland et al. 2007) by mobilizing pragmatic boundary objects (Carlile 2002) in order to effectively trade, intercalate and benefit from heterogeneous knowledge. In N-dimensional innovation spaces, digital technologies can become *transformative devices* by helping each of the members to define their unique knowledge in ways that relate to and build on each other's ideas (Boland & Tenkasi 1995). Because actors who are distributed, partisan and embedded often "run in packs", these digital capabilities must be configured in ways that allow for shared and co-present innovation runs [Van de Ven].

3.2.5. Locus of Innovation

Digital technology can radically reduce communication costs, thereby making participation in the innovation process by distributed actors more affordable. Innovation processes can then become open source projects, utilizing crowds to generate ideas. This openness brings a fundamental shift in the locus of innovation. As shown in Figure 8, we are increasingly seeing organizations and innovators moving to doubly distributed forms that substantially differ from vertically integrated, single sources of innovation (Yoo et al. 2008). New forms of innovation such as open source and crowd sourcing move the locus of innovation from inside an organization to its edges and periphery [Malone]. The de-centering of innovation activities pushes intelligence toward the edge of the organization's enlarging network.

De-centering the locus of innovation goes beyond a simple geographical dispersion. It reflects the looser coupling of the digital service architecture and the heterogeneity of knowledge required by the convergent and generative dimensions of digital innovation, as we discussed above. For example, many of the innovations spurred by Apple's iPhone came from thousands of app developers, rather than Apple itself. While Apple played a significant role in creating the digital platform with iPhone and iTunes stores, it was the small developers at the fringe of Apple's innovation network that produced the application innovations. In this case, their distributed innovation activities increased the social heterogeneity of the innovation network, which in turn, led to unbounded digital innovations.

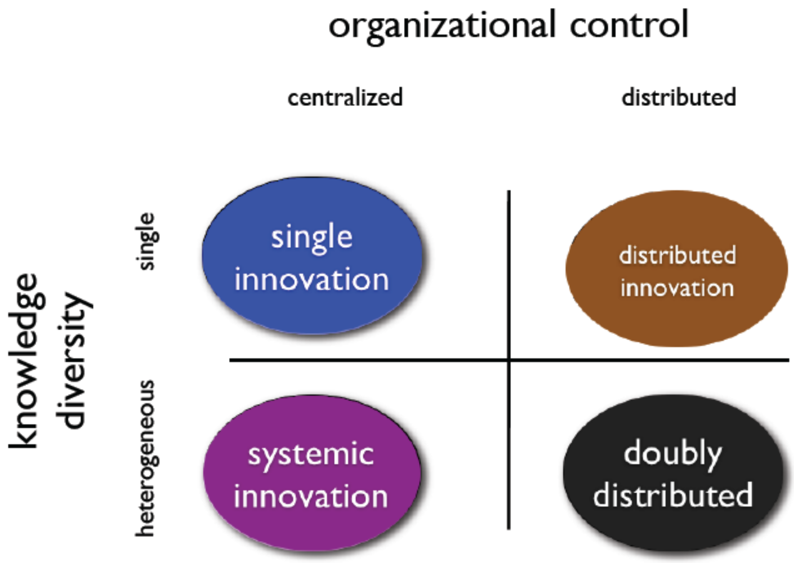

Figure 8. Emerging organizational forms of digital innovation (Yoo et al. 2008)

De-centering the locus of innovation has lead to the emergence of "just-in-time" innovation through on-going conversations among distributed innovators, with digital technologies serving as generative memory [Garud, Kumaraswamy & Tuertscher]. De-centering of the locus of innovation activities can be found in practices such as leaderless communities [Johnson], off-shoring and distributed design practices [Leonardi, Barley & Bailey; Helper], and self-organizing for innovation [Tuomi]. Future digital innovation processes must accommodate the emerging material and social limitations of de-centered, distributed innovation processes [Carlile & Lakhani; Majchrzak Birnbaum-More & Faraj].

Another challenge caused by de-centering the locus of innovation involves the governance of intellectual property. Digital innovation stimulates a shift from hierarchical and centralized forms of control, where value is created through a single locus of ownership, to distributed and horizontal coordination of value creation. Depending on the tasks and the nature of the actors involved, different forms of distributed coordination can be used [Malone] (see Figure 9). The dialectics between cooperation and competition are now being re-formulated into more dynamic systemic relationships, highlighting the simultaneous presence of competition and cooperation within a shared platform [Straub]. In newly de-centered innovation spaces, architectural control points and alternative forms of value extraction become an important strategic innovation [Henderson; Woordard & West]. A key challenge of control point architecture is to balance the tension between value creation and value capturing with appropriate forms of intellectual property governance. The new digital platforms and their architectural controls, increasingly act as "business platforms" that foster new forms of organizing … "empowering the edge" of organizations [Henderson].

Another research issue in digital innovation is whether distributed innovation design principles that worked effectively within purely digital innovation domains, such as software development, will work in new domains of digital innovation that involve physical products with embedded software capabilities [Tuomi].

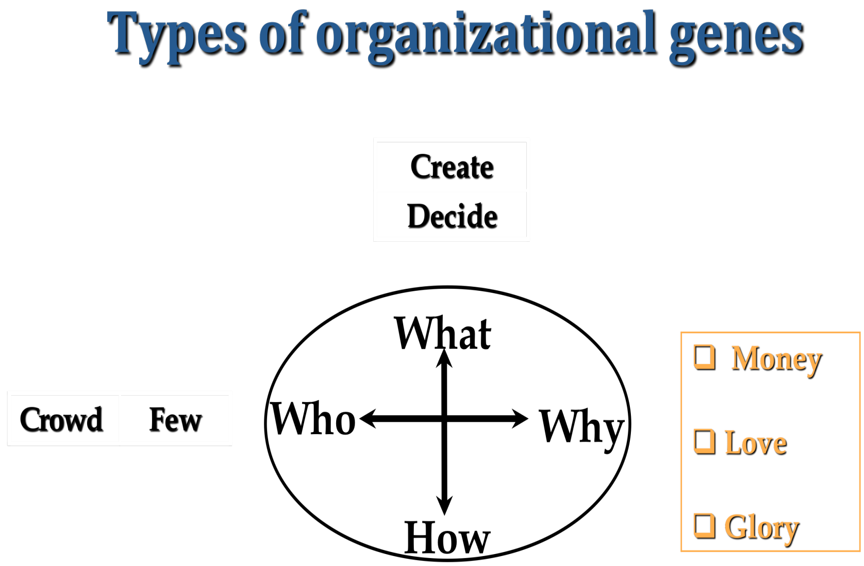

Figure 9. Types of organizational genes of distributed innovation [Malone]

3.2.6. Pace

By pace, we mean the rate at which change is enabled within a digitized platform. The phenomenon of pace has been well known in the research community since Mendelson and Pillay's (1999) study of the "clock-speeds" of industries. Pace includes how frequently organizations need to innovate, the speed of innovation they allow, and the required speed of diffusion. The increased pace in all digitized domains has resulted in a situation in which innovation needs to be continuous, relentless, and fast. Furthermore, the pace accelerates every year – moving toward a condition of singularity in our digital age (Kurzweil 2006).

Several workshop participants observed the effects of digitizing on the pace of innovation and its temporal characteristics. For example, Bowker noted that "we're going through a period of rapid digitization. What we're experiencing is something which has been going on for about two hundred years as far as databases are concerned" [Bowker]. It was argued that "the pace and nature of embedded digital technologies depends on industrial, organizational and work practice-level factors. For example, an industry with a high pace of change will lessen the role of seniors and increase the role of digital artifacts" [Bailey & Leonardi]. Furthermore, the digitized database and various forms of contents can fundamentally change the temporal dynamics of the creation of new artifacts and ideas. Bowker noted that:

> *"…the problem is seen in the Thesaurus Linguae Graecae (TLG) which was produced out of UC Irvine in 1985. The first edition came out in 1985. What it does is provide the complete canon of classical Greek literature in a single searchable database. What you would have to spend a whole career doing in the past, like going from library to library searching out each use of the word 'agape' to really find out what 'agape' means in terms of platonic love, you can now do at the punch of a button. I met a classic scholar several years ago who said that the TLG was absolutely marvelous. Now people can do things way, way quicker, but they're doing the same damn thing.*

They're not using it to ask new questions. They're not thinking with the new technology. They're not thinking with the possibilities of the new technology" [Bowker].

As Bowker's quote exemplifies, digital innovation represents unprecedented opportunity, but many challenges remain – and this is true for research as well as practice.

4. New Opportunities and Challenges

In this section, we review some new opportunities and challenges that emerge from digitalization. The presentation is an overview that seeks to highlight unique challenges associated with understanding the antecedents and consequences of digital innovation.

For this analysis, we make a distinction between *innovation outcomes* as something "new" being adopted and *innovation processes* that create and diffuse such outcomes. We seek to identify new opportunities and challenges in innovation outcomes and processes, and the specific aspects of digitalization that influence these opportunities and challenges. The summaries of this analysis are presented in table 2.

Table 2. New Opportunities and Challenges in Digital Innovation

Dimensions of Digitalization	**New Opportunities and Challenges**
Innovation outcomes • Convergence • Digital Materiality	**Dimensions of Convergence and Consequences:** • Dimensions of digital innovations through the emergence of unexpected combinations of four layers of digital service architecture • Underlying conditions and antecedents of digital innovation through convergence • Relationship between architectural control point and different forms of loose coupling across layers in digital service architecture **Digital Materiality and Entrepreneurial Opportunities**: • Different forms of digital innovations and new forms of entrepreneurial opportunities through embedding of seven characteristics of digital materiality **Digitalization of Innovation Practices, Tools and Capabilities:** • Reciprocal relationship between digital innovations in products and services and digitalization of work practices and innovation capabilities • Design characteristics of design platform to increase social heterogeneity and sustain generativity • Distributed geographical and temporal scale and scope of innovation processes • New forms of risks in digital innovation practices
Innovation processes • Heterogeneity • Generativity • Locus of Innovation	**Evolutionary Pattern**: • Chaotic, emergent, multiple and simultaneous nature of unbounded innovation • Socio-technical antecedents of wake-like, unbounded, and generative innovation • Architectural control point and the dynamics of unbounded digital

• Pace of Innovation	innovation processes • Strange attractors • Importance of periphery and blurred roles and dynamics among heterogeneous actors • Ambiguous and dynamic target populations **Temporal Dynamics of Digital Innovations**: • Relentless and increased rate of innovation • Antecedents and consequences of accelerated pace of digital innovation • Temporal coordination among heterogeneous actors in digital innovation network • Temporal dynamics in multi-modal, multi-source fast-paced digital innovation **Evolution of the Focal Firm and Platform with Digital Innovation**: • Developments in digital and physical materials as endogenous events • Alignments across material, cognitive, organizational, and identity layers of innovation • Reciprocal dynamics across four layers of innovation

4.1. Innovation Outcomes: Design

The main challenges and opportunities for innovation outcomes emerge primarily from convergence and digital materiality. The presentations and discussions at the workshop suggest that significant new opportunities lie ahead in defining different forms of digital convergence, along with their different dimensions. Specifically, we need to explore the following questions with regard to convergence:

1) How do we identify and describe conditions that generate new convergent products and services?
2) What are different forms of digital convergence? How do we define and measure digital innovations derived by convergence?
3) What are organizational, structural, strategic and industrial consequences of convergence?
4) What are different forms of architectural control and their impact on different forms of loose coupling across contents, services, networks and devices?

Precisely understanding the unique characteristics of digital materiality provides another key opportunity for future digital innovation research. Here, important questions focus on the identification of new entrepreneurial opportunities that emerge from embedding digital capabilities into non-digital products and services. In this regard, future research needs to explore the following questions:

5) What new forms of entrepreneurial opportunities are created, by embedding digital capabilities into existing products and services? How do we define and measure those digital innovation opportunities?
6) How will digital materiality, embedded in the form and function of products and services, affect organizations, innovation networks, and their architectural control?

7) How do digital and physical materiality interpenetrate to enable new digital innovations?

Finally, due to the self-referential nature of digital technology, digitalization of products and services also involves the digitalization of work practices and innovation capabilities. The increased use of digital tools and the interpenetration of digital and physical materiality in work practices, offer new sets of challenges that deserve careful investigation, including the following questions:

8) What are the consequences of digitalization of products and services on innovation practices, tools and capabilities in organizations?
9) What are the design requirements for an innovation platform to support sustainable unbounded innovation?
10) What are the social, economic and technological risks associated with the integration of digital materiality?

4.2 Innovation Processes: Dynamics

The main challenges and opportunities for innovation processes emerge primarily from heterogeneity, generativity, locus of innovation and pace. Future research on digital innovation needs to understand how these dimensions of digitalization influence patterns of innovation and diffusion, the temporal dynamics of innovation, and the evolution of a focal firm and platform.

The combination of heterogeneity, generativity, and distributed locus of innovation activity lead to the emergence of dynamic, non-linear patterns of digital innovation. Developing and validating analytic models to explore how heterogeneous actors at the periphery of digital innovation networks are related to innovation patterns will be an important challenge for innovation scholars. Scholars must understand different sources of unbounded innovations and their socio-technical antecedents. Specifically, future research needs to explore the following questions:

1) How do we model and analyze the chaotic, emergent, multiple, and simultaneous aspects of unbounded digital innovations in products and services? What new theoretical models and mathematics should we employ for explaining diffusion behavior, beyond our traditional linear models?
2) What factors underlie generative capabilities in different contexts? What are socio-technical antecedents of generativity?
3) What are the socio-technical dynamics of generativity in digital innovations?
4) How do we analyze the sporadic interactions between heterogeneous actors, networks and processes that affect digital innovation?
5) What are the different forms of loose coupling across contents, services, networks, and devices, and what are their effects on the dynamics of unbounded innovations?

Understanding the temporal dynamics of digital innovations provides another important opportunity for future innovation research. As noted earlier, we expect that the pace of innovation will accelerate with digitalization. Understanding the antecedents and consequences of such radical changes in the pace of innovation will be important. Furthermore, given the increased heterogeneity, distributed locus of innovation and the incessant pace of innovation, temporal coordination among different actors who share the same platform will become a major challenge. Specifically, future research needs to explore the following questions:

6) How do we analyze the increased pace of digital innovation and its diffusion processes?
7) What are the antecedents and consequences of an accelerated pace of digital innovation?
8) What are the temporal coordination mechanisms among heterogeneous actors who need to coordinate their actions while facing rapidly shifting boundaries, structures and outcomes?

Finally, the extant literature reveals that digital innovations are often quite disruptive to an organization and the organization often needs to go through fundamental transformation (Benner 2007; Benner 2010; Henfridsson et al. 2009; Lavie 2006; Tripsas 2009; Tripsas and Gavetti 2000). Such transformation, however, involves multiple layers that are interrelated (Henfridsson et al. 2009). First, a *material layer* refers to the tangible instantiation of a particular design embodied in artifacts. The artifact can be seen, heard, touched, and used; it performs a set of specific functions that create value for its user (Baldwin and Clark 2000). Second, a *cognitive layer* refers to the blueprint of an artifact and represents the mental schema that underpins the structure and functions of the artifact that is being designed. For instance, it specifies the hierarchical relationships and interdependences among design elements (Simon 1962). In addition, it specifies the relationship between general patterns of design and particular instances of that pattern (Alexander 1979). Third, an *organizational layer* refers to activities performed by various designers and their interrelationships (Sanchez and Mahoney 1996). It describes the design process and links design activities with particular units in organizations. Finally, an *identity layer* refers to the shared understanding by organizational members and outside constituents regarding what is central, distinctive, and enduring about an organization (Tripsas 2009).

An emerging body of research shows that these layers do not evolve at the same time, although all layers are likely to be influenced by digitalization (Henfridsson et al. 2009; Tripsas 2009). Therefore, changes in the material layer of digital technology will cause significant tensions in other layers, and successful digital innovation requires effective changes in the material layer, as well as carefully orchestrated changes in the cognitive, organizational and identity layers. The problem is further exacerbated because changes in the material layer often involve multiple, loosely coupled stacks of contents, services, networks and devices, involving multiple actors who are also going through internal changes. Future research should explore the multi-layered nature and evolutionary dynamics of digital innovation, both within a firm and across a digital platform network. Specifically, future research can explore following questions:

9) Are their evolutionary patterns in the four layers of innovation associated with digitalization?
10) What are processes and mechanisms by which organizations align the four layers during digital innovations?
11) How do firms deal with multiple and conflicting meanings of products and services as its cognitive layer evolves due to digitalization?
12) How do firms deal with the conflict between traditional hierarchical control, based on modular structures, and the emerging lateral coordination among distributed actors focusing on different stacks in the architecture?

13) How does organizational identity evolve as it faces unbounded innovations?
14) How does evolution in the cognitive, organizational and identity layers influence the design choices in the material layer?
15) How do we characterize the innovation trajectories and interactions between path dependency and the path creation enabled by digitalization (Adomavicius et al. 2008; Funk 2006; Henfridsson et al. 2009; Luo et al. 2009)? What are the roles of architectural control in the simultaneous evolution of multiple firms in an ecology and the emergence of new forms of digital innovations?

Studying the evolutionary dynamics of digital innovations requires scholars to take material changes in technology more seriously. As noted earlier, past research on innovation often treated technological changes as an exogenous variable and as a random external shock to the organization. However, in order to fully understand the nature of digital innovations, scholars must embrace technology as one of the endogenous variables and carefully consider how changes in its material layer reciprocally interact with other layers.

5. Conclusions and Recommendations

In summary, the workshop identified six dimensions of digital innovation: convergence, digital materiality, heterogeneity, generativity, distributed locus of innovation, and pace. The workshop saw these six dimensions as interacting to produce continued, fundamental changes in digital innovation outcomes and processes. Innovation outcomes are the digitalized products and services we encounter everyday, and they are primarily associated with the dimensions of convergence and digital materiality. Innovation outcomes include the emergence of a four-layered, digital service architecture for all types of digitalized products. The four layers are: devices, networks, services and contents, which are loosely coupled across the four layers. Loose coupling across the four layers sets the conditions for expansive, unbounded innovation processes. These new innovation processes, in turn, are primarily associated with the dimensions of heterogeneity, generativity, locus of innovation and pace. The new innovation outcomes and processes require different approaches to scholarship. Below we outline several preliminary suggestions for them.

5.1. Promotion of Multi-disciplinary Research

In order to study emerging phenomena of digital innovations, we need new, broader forms of scholarship in teams. The impact of digital innovation goes far beyond traditional domains where computer and communication technology has played important roles. The pervasive and ubiquitous nature of digital innovation suggests that we can expect to see digitalization in fields where computers and communication technology had previously been considered unimportant. This suggests that effective research on digitalization requires a tight collaboration between scholars of digital technology (computer science, information technology and information sciences) and scholars who have domain expertise in the newly relevant fields.

Because digitalization means more than mere technical digitization, and includes broader socio-technical reconfigurations, organization science scholars who have expertise in social and organizational change, psychology, and economics should also become involved in the expanded research teams. Overall, analysis of the workshop suggests that we need to promote multidisciplinary research approaches that include scholars from at least three domains: the subject domain field, digital technology, and organization theories of change and innovations. Teams of scholars can engage in multi-disciplinary research programs that have social and economic implications in such areas as energy, environment, public infrastructure, transportation, and healthcare.

5.2. Design Scholarship

Research on digital innovation is concerned with a wide range of novel ideas implemented with digital technologies. We believe research on digital innovation necessarily needs to take the form of what H. A. Simon refers to as the *Science of the Artificial* (Simon 1996). Such a scientific approach would seek the goal of *designing* a preferred state of affairs, rather than *describing* current conditions, and would deal with indefinite, unbounded innovation opportunities, rather than solving a current problematic situation. Design scholarship explores the creation of the new, and asks "*what might be?"* instead of tr "*what is?"*

Current scholarship on innovation is modeled after the natural sciences. In order to promote design scholarship that envisions new socio-technical structures and novel digital artifacts, we need different approaches to validation, measurement, modeling and analysis. Scholars in multiple field should explore different ways to conduct design scholarship. We believe a cross fertilization among academic communities that are open to explore design science opportunities will be an effective starting point in such efforts.

5.3. Multi-methods Approach

Studying emerging issues of digital innovation is likely to require more than one method, as scholars will have to grapple conflicting goals simultaneously. Scholars will have to have a deep understanding of technology, yet should not fall into technological determinism. Scholars need to understand the intimate local and material aspects of digital innovation, as well as their underlying generative mechanisms and principles. Scholars must be able to account for complex, emergent, and non-linear aspect of digital innovations, as well as see recurring patterns and orders. Scholars must consider technical, social, economic, legal, cultural, organizational and psychological antecedents and consequences of digital innovations, which requires empirically-grounded thick description, as part of theory-generating, qualitative research. At the same time, the proliferation of digital artifacts in products and services will create an unprecedented volume of data to be analyzed using quantitative research methods, which will require the development of novel analytical techniques. Yet, in spite of the increased breadth and inventiveness required of our research, we need to produce more timely results, requisite for the accelerated pace of digital innovations.

Recent theoretical and methodological developments based on computation techniques such as complex adaptive systems (Miller and Page 2007), network analysis (Christakis and Fowler 2009; Lazer et al. 2009), and sequence analysis (Abbott 1990) are likely to yield useful insights on the need for multiple methods and novel analytic tools. These types of methods are particularly helpful in modeling and analyzing the chaotic, emergent nature of digital innovation processes. They and related methods can be combined with historical research, data mining (see our recommendation below), ethnography, prototypes and laboratory experiments, among others, to produce powerful multi-method combinations.

5.4. Taking Data Seriously

One of the main research opportunities identified in the workshop is the availability of unprecedented amounts of data generated from all types of sensors, GPS tracking, processors and networks, forming a 'data deluge' [Bowker]. In certain areas, we are already seeing the emergence of truly massive data sets. Google's search database and many of the social network sites have already produced impressive amounts of data, which often lead to theoretical and practical insights. Lyytinen (2009) points out that in many different fields of inquiry, it is often the accumulation of large-scale, ultra-rich datasets, which are treated as a community asset, that has led to major discoveries. Large-scale scientific endeavors like sky mapping, ocean charting, human genome mapping, and climate change analysis all involve large-scale databases.

With pervasive and ubiquitous digitalization, we will be seeing a similar, if not larger, explosion of data. If it is properly regulated and managed, it can lead to unprecedented insights on human behaviors in our increasing complex socio-technical world. For example, many recent insights on human social behaviors are based on readily available on-line social network data. With digitalization of previously non-digital products and services, we face a unique opportunity to gain a deeper level of insights about human behaviors and socio-technical systems.

Currently, such data sets are being created and managed by private entities like Google, Amazon, Linden Labs, and E-Bay. Scholars should to try to assemble large-scale, ultra rich data sets from pervasive and ubiquitous digitalization of our social and economic activities and make them available in the public domain to support more systematic scholarly activities.

5.5. Infrastructure

Many of the opportunities of digital innovations are based on the continuing availability and growth of a digital infrastructure. Current scholarly activities studying various aspects of infrastructure and its role in digital innovation still remain at the fringe of many of the fields that are related to this research. For example, organization science and technology management are two main fields that study innovation. Yet, mainstream scholars are not conducting significant amounts of infrastructure research. More scholars should systematically pursue how infrastructure innovations emerge and how they in turn spur innovations in other areas. In particular, they should focus on tracing the emergence, formation and evolution of infrastructures in different industries and professional fields to their impacts on digital innovation processes and outcomes (e.g., standards, coordination, and combinative capabilities).

5.6. Theorizing Digital Technology

The emergence of four-layered, generic, digital service architectures as platforms for all types of digitalized products and services imply that more of our economic activities will be mediated through digital technologies. Furthermore, digital convergence suggests that markets that had previously been separated, will increasingly overlap. For example, VoIP technology that is from the computer network industry is rapidly becoming a dominant technology in the telephone industry. Similarly, many parts of the computer, IT, or communication industries are becoming parts of other industries. Therefore, from a digitalization standpoint, many of the economic sectors that are currently classified as separate sectors might need to be considered together.

Current popular industry classification schemes, such as NAICS and SIC codes, however, do not reflect the pervasive and ubiquitous nature of digital technology in a coherent way. For example, many companies that produce physical devices are listed under the manufacturing sector, while companies producing the contents layer are listed under an information sector. However, if digitalization continues in many other sectors and the nature of the devices and contents change over time, it is not clear how the current industry classification system can handle such fundamental changes.

We believe that we need a complementary classification scheme that reflects a digital architectural perspective, rather than our traditional product-centric view that assumes tight coupling across different layers. In order to establish such a classification scheme, however, we need more refined theoretical models of digital service architectures. We hope that what we offer in this report, combined with results from other parallel attempts to explore the phenomenon of digitalization, can serve as a useful starting point.

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Appendix A: List of Participants and Presentations

1. Robert Austin (Harvard University), “Digital Technologies and Process Structure: Re-arranging Production for Post-Industrial Value Creation.”
2. Diane Bailey (University of Text at Austin) & Paul Leonardi (Northwestern University), “The computer’s manifold role in product design: Differences in advanced technology use across three engineering occupations.”
3. Richard Boland (Case Western Reserve University, Co-PI).
4. Geoffrey Bowker (Santa Clara University), “Rapid digitization and innovation research: The case of databases.”
5. Paul Carlile (Boston University) & Karim Lakhani (Harvard Business School), “Addressing the challenge of novelty in distributed innovation: Stretching from open source software to drug discovery.”
6. Jonathon Cummings (Duke University), “Membership intensity and innovation performance in geographically dispersed teams.”
7. Deborah Dougherty (Rutgers University), “Intertwining multiple sciences, digital technologies, and strategies for drug discovery.”
8. Samer Faraj (McGill University), “Innovation and network morphology on the Web.”
9. Raghu Garud (Penn State University), Arun Kumaraswamy (Temple University), & Philipp Tuertscher (Vienna University of Economics and Business Administration), “Facilitating asynchronous, distributed collaboration using digital technologies”
10. Sue Helper (Case Western Reserve University), “Viewing off-shoring through a relational lens: The case of automotive product development.”
11. John Henderson, (Boston University), “Design principles for business capability platform.”
12. Ola Henfridsson, (Viktoria Institute) and Lars Mathiassen (Georgia State University), “Digital convergence dilemmas in manufacturing: The emergence of distributed innovation capability.”
13. Suzi Iacono (National Science Foundation), “Digital Innovation Research Opportunities at National Science Foundation.”
14. Markku Ilvesmaki, (Nokia), “Device convergence and radical digitization.”
15. Sirkka Jarvenpaa, (University of Texas at Austin), “Ownership behavior of content creations on Web 2.0.”
16. Steve Johnson (Temple University), “Leadership in leaderless organizations.”
17. Karim Lakhani (Harvard University) & Ned Gulley (The Math Works), “The determinants of individual performance and collective value in private-collective software innovation.”
18. Paul Leonardi (Northwestern University), Steven Barley (Stanford University), & Diane Bailey (University of Text at Austin), “Car crashes without cars: Considering the role of abstraction in digital innovation.”
19. Kalle Lyytinen (Case Western Reserve University, Co-PI), “Information Infrastructure and Digital Innovation.”
20. Tom Malone (MIT), “Toward an organizational genome bank: Classifying and designing collective intelligence.”
21. Ann Majchrzak (University of Southern California), Philip H. Birnbaum-More (University of Southern California) & Samer Faraj (McGill University), “Facilitating knowledge development in agile emergent innovative groups.”
22. Detmar Straub (Georgia State University), “Cooperative-Competitive dynamics in the eBay digital network.”

23. Burt Swanson (University of California, Los Angeles), Researching Web 2.0."
24. Ilka Tuomi (Meaning Processing Ltd.), "When innovation is hard – Open innovation in open cores."
25. Andrew Van de Ven (University of Minnesota), "Knowledge production in distributed innovation networks."
26. Jason Woodward (Singapore Management University) & Joel West (San José State University), "Architecture and control in digital innovation networks."
27. Jennifer Whyte (University of Reading), "Model risk, digital innovation and complex organizations."
28. Youngjin Yoo (Temple University, Co-PI), "Digital challenge in innovation research: Why are we here and what do we want to achieve?"
29. Shaker Zahra (University of Minnesota), Nachiket Bhawe (University of Minnesota) & Alok Gupta (University of Minnesota), "Digital convergence and the birth of new business."